THE DIFFERENT TYPES OF CORROSION PROTECTION USED AT THE RANCE TIDAL-POWER STATION

Jacques Lefrancois

(NASA-TT-F-16101) THE DIFFERENT TYPES OF CORROSION PROTECTION USED AT THE RANCE TIDAL-POWER STATION (Scientific Translation Service) 36 p HC $3.75 CSCL 07A N75-14886
G3/26 Unclas 07731

Translation of "Les differents types de protection contre la corrosion mis en oeuvre a l'usine maremotrice de la Rance", Colloque International Cefracor 74, Centre Français de la Corrosion, La Baule, June 4-7, 1974, pp. 1-18.

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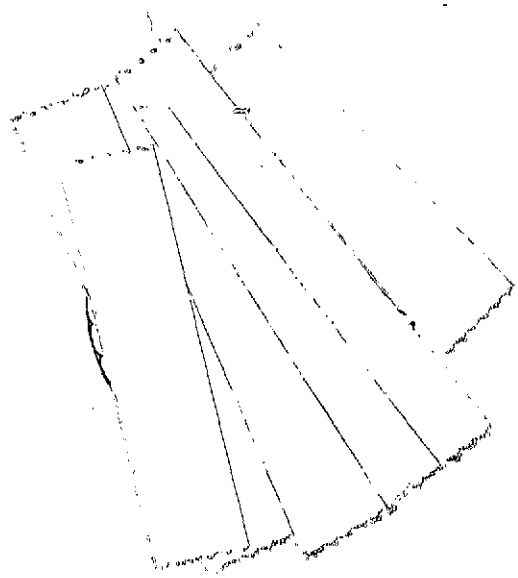

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 JANUARY 1975

STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TT F- 16101		

4. Title and Subtitle	5. Report Date
The Different Types of Corrosion Protection Used at the Rance Tidal-Power Station	January, 1975
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Jacques Lefrancois	10. Work Unit No.

9. Performing Organization Name and Address	11. Contract or Grant No.
SCITRAN Box 5456 Santa Barbara, CA 93108	NASw-2483
	13. Type of Report and Period Covered
	Translation
12. Sponsoring Agency Name and Address	14. Sponsoring Agency Code
National Aeronautics and Space Administration Washington, D.C. 20546	

15. Supplementary Notes

Translation of "Les differents types de protection contre la corrosion mis en oeuvre à l'usine maremotrice de la Rance", Colloque International Cefracor 74, Centre Français de la Corrosion, La Baule, June 4 - 7, 1974, pp. 1 - 18.

16. Abstract

It is shown that cathodic protection used in conjunction with paints and metallizations has been very effective in controlling corrosion of submerged metallic structures at the Rance tidal-power plant.

PRICES SUBJECT TO CHANGE

17. Key Words (Selected by Author(s))	18. Distribution Statement
	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	36	

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ANNOTATION

The presence of sea water and salt air is one of the factors characteristic of the Rance tidal-power station. The metallic structures must be carefully protected from electrochemical corrosion.

Investigations carried out up to 1966 showed a number of corrosion protection methods which can be summed up in four points:

1) Rules to be observed during design, fabrication, and installation of components.

2) Choice of basic material for components immersed in sea water.

3) Use of coatings or surface treatments.

4) Use of cathodic protection by applied current (and infrequent application of soluble zinc anodes).

Conclusion:

After seven years of operation, it can be said that cathodic protection plays an essential role in keeping the tidal-power plant functioning well. Hand-in-hand with other techniques, cathodic protection very efficiently protects 12,000 metric tons of steel immersed in sea water, carbon steel as well as stainless steels subject to pitting corrosion.

This protection allows repainting to be spaced out, if not avoided, which contributes to reducing down-time of the equipment and to increasing the profitability of this tidal-power plant.

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DIFFERENT TYPES OF CORROSION PROTECTION USED AT THE RANCE TIDAL-POWER STATION

M. Jacques Lefrancois, E. D. F.

ABSTRACT: It is shown that cathodic protection used in conjunction with paints and metallizations has been very effective in controlling corrosion of submerged metallic structures at the Rance tidal-power plant.

Metal Corrosion at the Rance Plant

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The presence of seawater and salt air is one of the factors /1** characteristic of the Rance plant, and ever since studies began it has been apparent that the metallic structures of the station would have to be carefully protected from electrochemical corrosion.

The engineers responsible for the project have been fully conscious of this problem, and as early as 1955 they set up a study group with an experimental laboratory at Saint-Malo, under conditions identical to the future operating conditions, whose

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* Head of the Brittany Mixed Working Group.

** Numbers in the margin indicate pagination of original foreign text.

Photo No. 1. The Rance barrage: general view.

task was to find the most effective methods of protection.

These studies, pursued without interruption until 1966, have revealed a series of methods to be used in corrosion protection, both in the shape of precautions to be taken in the manufacture of components, or in terms of usage of materials and supplementary techniques.

In particular, these include:

— a set of rules to be followed in the design, manufacture, and installation of components;
— choice of basis materials for immersed components;
— use of coatings or surface treatments;
— use of cathodic protection.

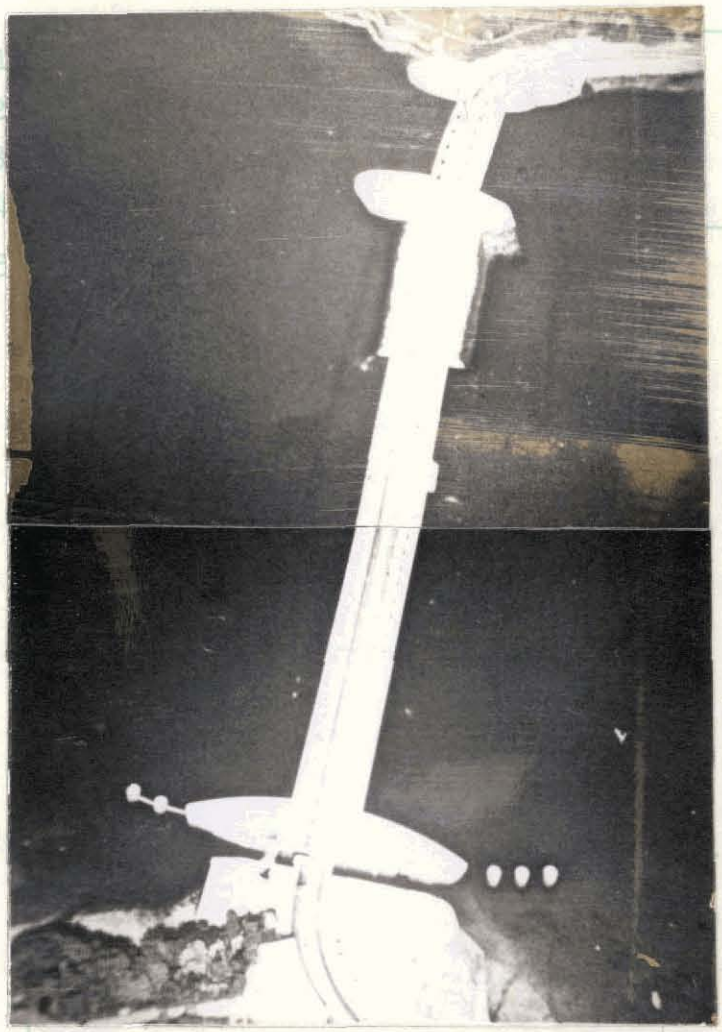

Photo No. 2. The Rance barrage: from top to bottom: the six gates, the dam, the "plant barrage", and the lock.

In this paper we shall take up each of these techniques, to show where and how it has been used and, in the light of the considerable experience available after eight years of operation, to try to determine whether it is effective, and met our expectations.

1. Rules to be observed in /2 the design, manufacture, and installation of components.

1.1. It is well known that when an electrolyte is present, contact between two different metals must be avoided, lest a couple be formed which will activate corrosion. Following this rule has led to problems — often difficult — in mixed structures composed of carbon steels, stainless steels, and non-ferrous metals and alloys.

One is obliged to provide electrical insulation between parts whenever the electrolytic couple exceeds 50 mv. To give only one example, the austenitic stainless-steel gate rollers were electrically insulated from the plain carbon steel superstructure because the potential difference in this case is 240 mv.

Following this rule has also required special precautions for castings: the micro-structure must be as homogeneous as possible since any heterogeneity creates a local couple.

Other risks are less well known; for example, those presented by overlaps between parts, assembly by riveting, complex shapes and any arrangements which create metallic surfaces in contact with stagnant water — water less oxygenated than the moving sea water. This difference in oxygenation may produce particularly aggressive corrosion of stainless steels: corrosion due to differential aeration.

It was also necessary to think about the proper adhesion of the protective coatings, and to avoid sharp angles by careful grinding of weldments.

Finally, attention was given to the effect of surface condition and harm resulting from contamination of unpainted surfaces by foreign metallic particles (pieces of oxide, debris from machining tools).

1.2. After only a few months of operation of this plant, experience showed us the importance of these rules. We could see that every time they were forgotten or could not be applied, there rapidly appeared an attack on the metal which was more serious the more localized it was.

This was particularly the case for the corrosion found very early on the connecting flanges of the devices which control the flow of seawater for moistening the seals. This attack was an example of the corrosion of stainless-steel parts due to differential aeration, non-oxygenated water having been able to seep between the two flanges.

2. Choice of basis materials /3

2.1. It would obviously be handy to be able to use a material which is perfectly resistant to seawater corrosion and which has excellent mechanical properties. We can say immediately that this material was not known; even disregarding considerations of cost, it would have been impossible to find it, since high-chromium stainless steels which come closest to it are still subject to certain types of corrosion, while the synthetics which are excellent with respect to chemical inertness do not have high mechanical properties.

It has thus been necessary to find the material which best suits each application. Despite their relatively high cost, stainless steels and bronzes were widely used, since out of a total weight of 550 metric tons for a turbogenerator at the Rance plant, these materials account for about 230 tons. Tehy are found especially:

— inside hydraulic ducting where adhesion of coatings is uncertain;
— for certain mechanical components which could not be protected because of their function, wear or sliding;
— for piping which must carry seawater.

Among the materials used, we may note:

2.1.1. Austenitic steels containing 18% chromium and high in nickel (11 to 12%). With low mechanical properties but having the high elongation needed for welding, these steels in the VIRGO 14SS quality from S.F.A.C. have been used for almost all the sheet-metal work.

Austenitic 19-8 steels, lower in nickel, have also been used for the cover and the supports of the carbon seal and for the

moving labyrinth. The seawater piping inside the turbogenerator is made from this type of steel.

2.1.2. Martensitic steels, type Z05 CND (17% chromium and 4% nickel), which were widely used in qualities VIRGO 39 from S.F.A.C. and NSPM from Ugine for large machined components and for components which are highly loaded in seawater. Some of the blade assembly, the guide vanes, the arbors of the blade servomotors, and the turbine cones are of this type of steel. /4

In these steels, as for the austenitic steels of the preceeding paragraph, a small molybdenum content (1 to 2.5%) improves corrosion resistance in salt water.

2.1.3. Aluminum bronzes. Copper-aluminum alloys containing 9 to 10% aluminum, 0.5 to 2% manganese, 4 to 6% iron, 4 to 6% nickel, such as INOXYDA 53H from Forges et Fonderies d'Alliage de Haute Resistance (High Strength Alloy Forges and Founderies, Petit Quevilly), have good mechanical properties and are claimed to be unaffected by corrosion due to differential aeration. They were used for about half of the blades and for various valves and different forgings in the seawater circuits.

INOXYDA 90 from the same foundry was used for the impellers, housings, and arbors of the sump pumps.

Brazed INOXYDA 3P sheet was used for various seawater pipings. Seals and fastners made of this material were used to attach the rollways of the gates (Photo No. 4).

2.1.4. Various synthetic products. Wherever their lower mechanical properties allowed it, attempts were made to use synthetic products in the piping. In general, PVC was used when only a limited amount of water could escape in case of rupture; otherwise, copper aluminum was used.

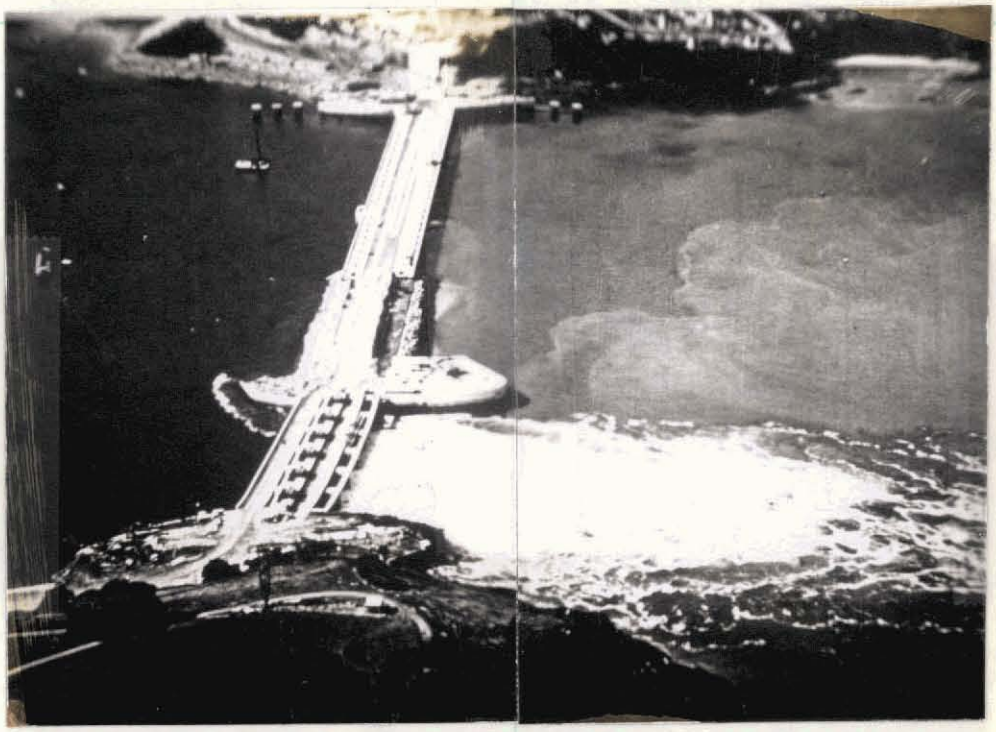

Photo No. 3. The flood flowing through the six gates of the barrage (end of basin outflow).

Photo No. 4. Interior of plant On the first floor are two turbine blades, one of aluminum bronze, the other of stainless steel: two spares which will not be used for a long time.

Photo No. 5.

Photo No. 6.

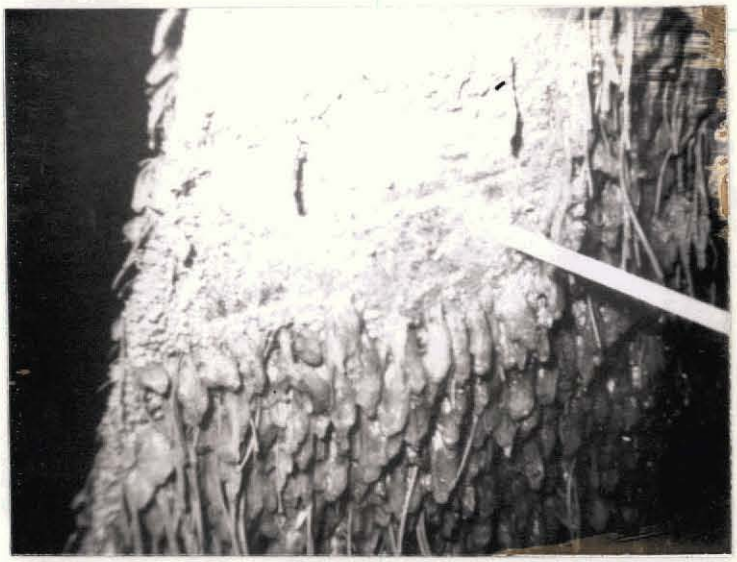

Photo No. 7.

Photo No. 8.

Photo No. 5. to No. 8: Condition of stainless steel blades of turbine 6 after immersion without rotation.

Photo No. 9. The same blade after cleaning and milling of the holes produced by corrosion.

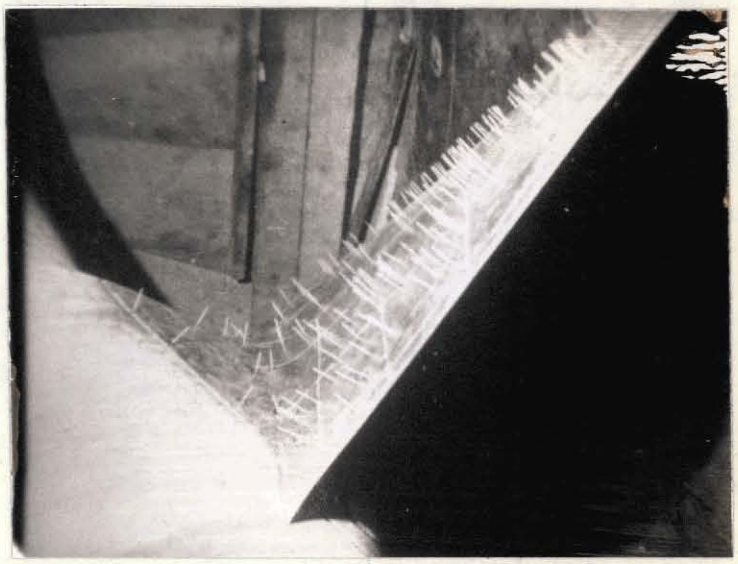

Photo No. 10. Bottom of the blade after inserting a match in each corrosion hole.

— "AFCODUR F" polyvinyl chloride pipe was used, for example, for the discharge of the sump pumps, for the discharge of the pumps for filling the seawater reservoirs, for the lines supplying seawater to the seals, and for the soft-water collectors for fire-fighting;
— polypropylene valves and tubing are at the ends of 48 pressure /5 pick-offs;
— rilsan tubing was used in the lubracation lines for the gates;
— nylon fastners were used when mechanical forces allowed, especially on the gates.

2.2. Remarks on the resistance of some of these materials.

2.2.1. 17-4 martensitic steel turbine blades (Photos 5 to 10).

Early inspections, after about 3000 hours of operation, showed good behavior of these blades with respect to both corrosion and cavitation.

There was, however, an incident of corrosion due to a phase of abnormal operation which is instructive of the poor resistance of these steels toward corrosion by differential aeration. Because of the inevitable time lags among the various phases of start-up at the plant, turbogenerators B5 and B6 were put into the water several months before their first operation.

During these periods of immersion without rotation, a very heavy deposit of algae and shellfish developed on surfaces which were not protected by anti-fouling paint, and especially on the blades. Then under the anti-oxygen layer which this deposit really is, corrosion by differential aeration developed, with very many points of pitting attack which required later repair.

2.2.2. Aluminum bronze turbine blades.

The good resistance of these copper-aluminum blades is perfectly confirmed today after 60,000 hours of immersion, especially in temrs of corrosion.

2.2.3. Austenitic stainless steel piping inside the turbines. /6

Attack on the metal which may result in penetration of pipe walls was seen locally but systematically on several turbines. The regions attacked lay near weldments, on either side of the fusion zone. It appears that this must be attributed to intergranular corrosion due to precipitation of chromium carbide when the temperature of the metal rose during welding.

When the temperature is above 400°, the carbon and the chromium initially dissolved in the austenite tend to combine to produce chromium carbide. The chromium is removed near the grain boundaries first; the metal in this region is particularly depleted of chromium and its corrosion resistance decreases.

This phenomenon is now well-known to corrosion specialists, and doubtlessly could have been avoided by using low-carbon steels (carbon less than 0.03%), Titanium-stabilized steels (titanium is more reactive with carbon than chromium and prevents formation of chromium carbide), or duplex austenitic/ferritic steels.

In fact, at the Rance plant, we at first limited ourselves to protecting the interiors of these pipes by araldite paints applied under difficult conditions; it later became possible to discontinue this to a large extent, and the remaining smaller-diameter pipe sections were replaced with synthetic material.

Other problems of different origin were found on the inlet tubing for the water for moistening the seals, in the immediate vicinity of the attachment to the water case and on the threaded flange which attaches these tubes to the unit. Seen for the first time on turbine 6 in January, 1968, this was very probably caused by differential-aeration corrosion of the lower part of the tubing, which was covered by mud. It was becoming a general problem throughout all the turbines, however.

To avoid very major disassembly, repair was carried out by covering the defective end of the tubing with a nylon sleeve about one meter long.

2.2.4. Copper-aluminum piping /7

Corrosion penetrating the wall has also been observed in 150-mm piping at the intake of the pumps distributing seawater for moistening the seals, and on piping of the same diameter which empties the hydraulic ducts of the turbines.

In these two cases the piping is made of 3P copper-aluminum from Forges et Fonderies d'Alliage at Petit Quevilly, 3 mm thick, rolled and welded.

Examination showed that this time there was generalized intergranular corrosion, and the results of analyses performed by the E.D.F. laboratory for Thermal Production, through disputed by the Petit Quevilly specialists, explained this attack by the phenomenon of de-aluminization of the alloy.

It also seemed that a secondary phenomenon, probably erosion caused by the velocity of the water in the pipes, had accelerated the process by removing the corrosion products. This hypothesis

allows an explanation of why, although these pipes are now used only from time to time, the failure is much less frequent than while the turbines were being installed, when they were constantly swept by leakage from the temporary cofferdams.

Failed pipes have been repaired by welding, except for the intake pipes of the seawater pumps, where "Fibercast" parts were tried. This German-made pipe is produced by centrifugation of epoxy resin onto glass-fiber reinforcement. The special nature of this armature gives the pipe remarkable mechanical properties, and the composition gives it exceptional chemical inertness; unfortunately, the cost is very high.

2.2.5. Plastic products and various synthetics.

Although it is not a matter of corrosion, but of inability of the products to sustain high mechanical loads, we should mention failure of the outlet pipes of the sump pumps. These large-diameter (250 mm) components were found to be incapable of holding the overpressure when the pumps stop (3.5 kg/cm^2), and the overpressure had to be relieved artificially.

There were also problems with the nylon fasteners used on the gates, especially those holding the cover on the lubrication resevoir. These fasteners seem to be working at the limit of their mechanical capabilities, and we have observed that many threads have been stripped.

3. Use of coatings or of surface protection. /8

It is desirable to distinguish between coatings obtained by application of a flexible protective film, essentially the paints, and those obtained by applying a metallic coating: galvanizing, chrome plating, or even those produced by modification of the

surface involved, as in anodization.

3.1. Paints

3.1.1. This is the best-known type of protection, and it is widely used at the Rance plant. Tests at St.-Malo have shown up the poor seawater resistance of ordinary paints and the importance of using more complex coatings which offer the following advantages in addition to much better resistance:

— better resistance to electrical action, and to the strong concentrations of alkaline products which result from application of cathodic protection;
— thinner coatings, which is important for the walls of the heat-exchanger.

The paints used can be divided into three wide classes:
— Coatings applied to structures which will undergo immersion (hydraulic ducts fo turbines, gates, lock gates, etc.). In the hydraulic ducts of the turbines it was accepted on principle that the plain-carbon steel components would be protected by paint alone. To reduce the size of the cathodic surfaces and current consumption in cathodic protection, it has been necessary to apply paint to the entire structure except the blades. For a total thickness of 165 µm, the coating contains:
  — a layer of phosphate wash primer to passivate the metal and improve adhesion of the coating proper;
  — three inhibitor layers composed of a vinyl binder with incorporated inhibitor pigments (zinc chromate)
  — two finish layers which have a dual function: to protect the layers below so they can display their inhibitory action, and by their antifouling action to prevent attachment of algae and larvae of marine animals to the coating.

— Coatings applied to structures which are not immersed, but are in contact with salt air. At the Rance plant, every surface which is not immersed is considered to be in contact with salt air. With a total thickness of 145 µm, these coatings are identical to the preceeding ones, except that the two finish coats, which no longer must protect from fouling, are thinner and give an unreactive finish. /9

The following are exceptions to this classification:

— Epoxy paint on the inner surface of the alternator frame. This particular paint was necessary to resist the high temperature needed for polymerizing the resins which bond the magnetic circuit.

— Plastigen paint used in two coats of 90 µm total thickness on surfaces in contact with hot oil.

— A paint containing zinc pigments in solution, used in three coats for a total thickness of 100 µm on the handling gangways of the polybloc cofferdams and on the cofferdams themselves.

From the beginning of the tests, attention was directed to the importance of the care to be taken in the use of vinyl paints, and especially to the surface preparation obtained by sanding with corundum (for plain-carbon steels) and by pickling (for stainless steels).

3.1.2. The metallic structures of the lock were put into the water in November, 1962, those of the gates in March, 1963, and finally the first turbines in March, 1966. We shall study the behavior of the paints on each of these three types of structure in turn.

3.1.2.1. Lock /10

When overhaul began, from 1967 on, the situation was as follows:

— On the upper part of the gates the antifouling properties of the outer layers had disappeared, and spotting began to occur, without penetration of the protective layers. In contrast, the lower two meters had localized but deep attack. The fasteners holding the seals were especially affected.

The work was undertaken without damming, on the tide and, for the lower parts, taking advantage of a considerable lowering of the basin. For the most part, the paint could be repaired by reconstituting the antifouling layers after cleaning; at the bottom, it was necessary to repaint all layers completely after sanding.

— The gates of the aqueduct were heavily attacked, especially that located on the seaside where the frame had been rusted through. The plates were welded to reinforce the frame, and the gate was completely repainted.

In conclusion, it is apparent from this work that localized but deep corrosion occurred on the lock, and it can reasonably be expected that proper maintenance of these installations will require more frequent attention. But there is:

— Difficulty in carrying out these operations on the tide in a lock which can be dammed only with difficulty because of the down-time which results.

— High costs. The 1967 repairs ran from March to November and cost nearly 10 million old francs.(1)

— Uncertainty about how long some of these repairs will last: they were carried out under conditions very different from the initial conditions (time available for work, limited drying time, work in humid atmosphere, difficulty of surface preparation).

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(1) Translators note: 100 old francs = 1 new franc.

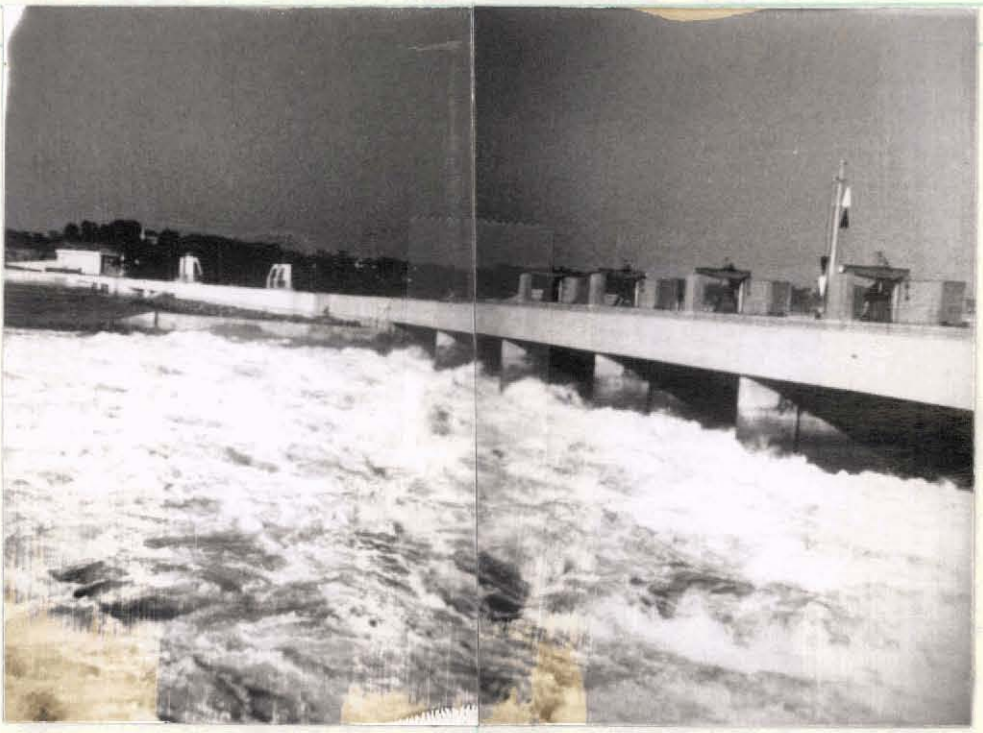

Photo No. 11. Gate top holes.

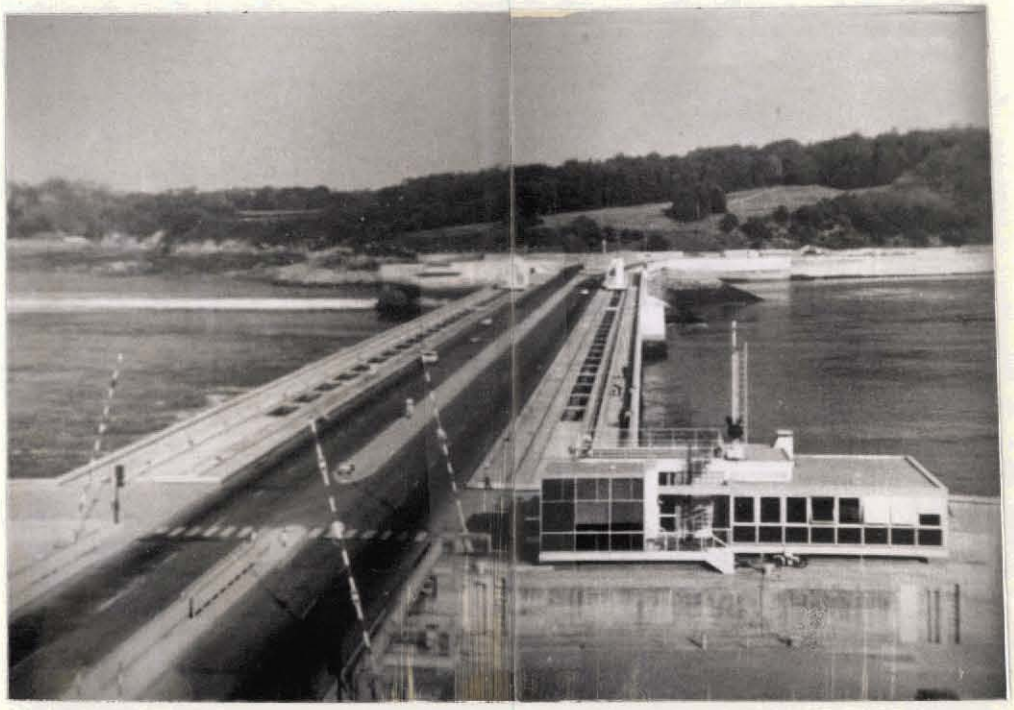

Photo No. 12. The administration building is covered with anodized aluminum sheet, as is the interior of the plant.

It is also to be expected that the vinyl films will adhere poorly to the irregularities of the corroded sheet metal.

— Good results obtained on the turbogenerators and gates with cathodic protection. It has been decided to ask Gaz de France to study a system for cathodic protection of the lock.

3.1.2.2. Gates (See Photo No. 11.) /11

The initial painting of the gates was the responsibility of the fabricator according to the contract, and was sub-contracted by him to a local applicator. This job was found to be defective to the point that from February, 1964, to July, 1965, the R.E.M. had to overhaul it completely.

During examiniation, it was found that the applicator was clearly at fault, so that it is difficult to draw any conclusion about the future durability of these paints from this experience.

However, in August, 1966, one could begin to see some incrustations of shells and localized traces of rust on gates 4,5, and 6, which had been repainted in 1964.

In August, 1967, the condition of gate 6 was quite conspicuous: the frame had many incrustations of shell-fish, acorn shells, calcified wormholes, and significant traces of rust.

Because a cathodic protection system for the gates was to be put into service in 1968, the work undertaken then was limited to localized retouching on gate 5 and to complete repainting of gate 6.

3.1.2.3. Turbogenerators

One cannot judge the durability of the paint on the turbogen-

erators without speaking of cathodic protection, since for most of them such protection was operative very soon after the hydraulic ducts were filled with water.

We shall thus look ahead to the following section to mention the beneficial influence of cathodic protection on the durability of the paints. Inspections have shown that one must expect many breaks in the protective film due to passage of foreign bodies and also to the inevitable scratches which occur during work.

Right at the largest breaks, the metal appeared bright and with no trace of rust; the rest of the coating was more or less well covered with a calco-magnesia deposit. We shall return to this later.

3.2. Metallic coatings

/12

3.2.1. Zinc

Tests have shown that deposits of zinc behave well in sea-water, and have the advantage of being self-healing by electrolysis of zinc at accidental holes in the coating. This very property prevents their use on systems such as the turbogenerators at the Rance plant, which contain significant amounts of noble metals, and where the consumption of zinc would be much too large.

Such is not the case with surfaces which are not immersed; for their protection zinc is widely used:

— as a thick coating, about 100 µm, deposited by hot galvanization on the metal frameworks and skeletons, especially the ironwork of the 3 kV cells.

— as a much thinner layer, about 2.5 µm, electrolytically deposited onto the sheets used for the frames, cabinets, and panels of the apparatus.

3.2.2. Cadmium

We shall say only that all suppliers require exclusive use of fasteners coated with dichromated cadmium.

3.2.3. Chromium

A coating of chromium more than 3/100 mm thick is considered to be sufficiently tight to protect the underlying structure from corrosion. Aside from the well-known hardness and wear properties of chromium, in certain cases this property allows a reduction in the amount of an expensive basis metal for a certain component. At the Rance plant, this coating has been used on the shafts of the jackscrews which operate the lock gates, the shafts of the aquaduct gates, and the shafts of the lift bridges, where a layer of chromium protects the plain-carbon steel.

During inspections in 1968, several of these shafts were seen to have localized failures consisting of a rupture of the chromium skin and a generally deep attack on the shaft, but it was impossible to determine which of these phenomena was the cause and which the effect.

Repair required replacement of the shaft, which was protected by 5/100 mm of plate over a nickel undercoat. This reduced the strength of the assembly, but led to a considerable improvement in its corrosion resistance; it was possible in this case because the mechanical loads are relatively low.

3.2.4. Anodized aluminum sheet (See Photo No. 12) /13

We should like to call attention to a use of anodized aluminum sheet, important from an architectural standpoint: in the

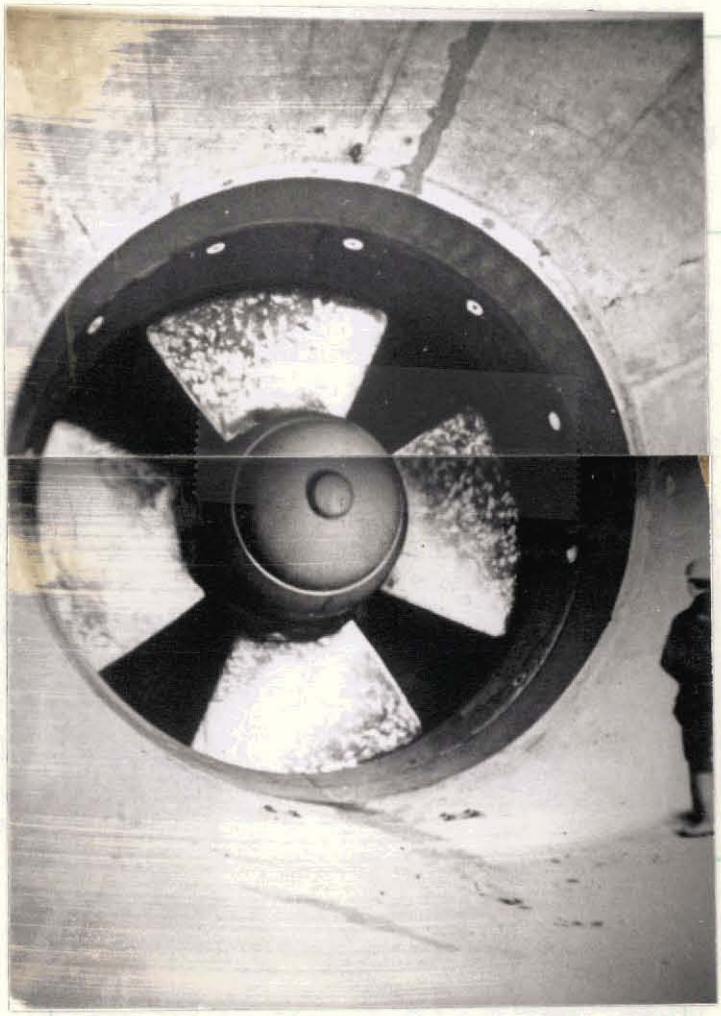

Photo No. 13. Turbine inside its hydraulic duct: 7 of the 12 anodes on the wheel casing are clearly visible.

interiors of the power plant and of the administration building. The anodic coating, which must be thicker than 15µm to withstand marine atmosphere, but can be as thick as 25µm, is obtained by electrolytic treatment in a sulfuric acid solution. The alumina layer so produced is porous and can easily absorb dyes, which is of value for decorative purposes.

4. Cathodic protection

4.1. Cathodic protection by applied current

4.1.1. Turbogenerators

(See Photos Nos. 13 and 14)

4.1.1.1. We have seen that, except for the blades, a particularly carefully-applied coat of paint protects all the metallic parts from contact with the seawater.

It was nevertheless obvious that this coating, located inside the hydraulic system, would be broken or damaged locally. The couple created by contact of stainless steel with plain-carbon steel would thus produce a significant acceleration of corrosion, which would appear right at each of these breaks.

It thus very quickly became apparent that is is necessary to place the whole metallic structure artificially into a region of potential where the reaction between metal and electrolyte is made impossible. This is what is required of cathodic protection.

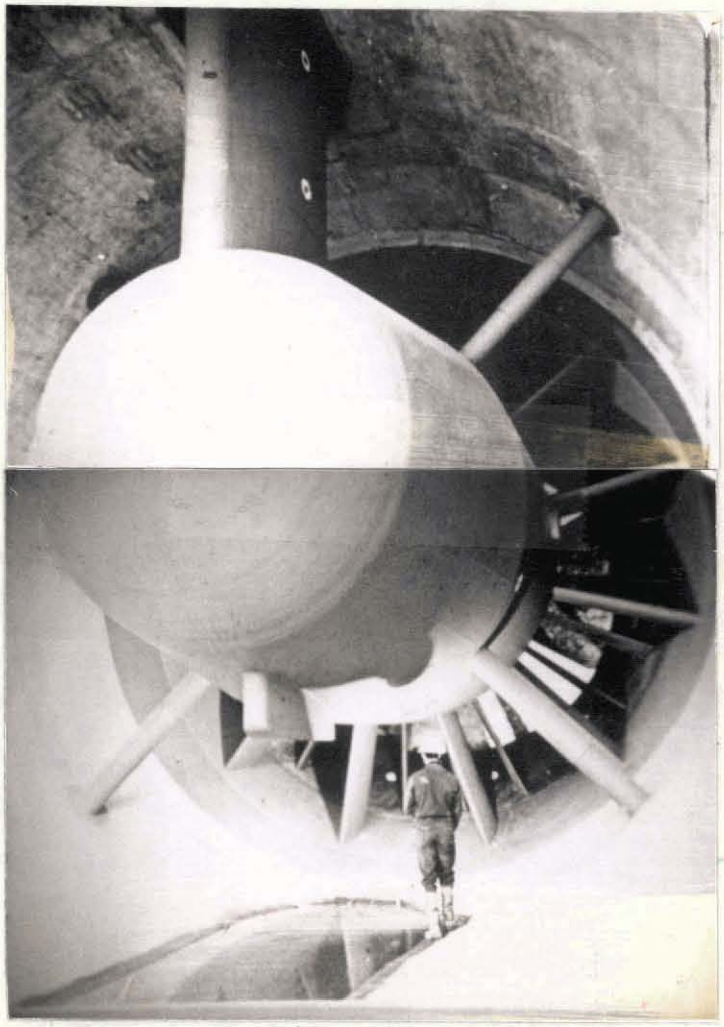

Photo No. 14. Two anodes are visible on the access arms (top of photo).

4.1.1.2. The apparatus consisted essentially of 36 anodes per turbine divided into:

— a ring of 12 anodes on the seaward side of the wheel casing;

— a ring of 12 anodes on the guide vanes;

— a set of 13 anodes consisting of a ring of 8 anodes on the tie-rod ring and 4 anodes mounted on the access arms.

These anodes are connected to the positive pole of a central DC supply for a set of 4 turbines, with separate current control for each of the three groups of anodes described above.

Three voltage test points /14 on each turbine allow adjustment of the potential of the metal wall at these points with respect to the seawater.

The supply is designed to provide a maximum current of 100 A at 20 VDC, to be divided among 48 anodes; each anode can carry a maximum of 4 A over an anode surface of 125 cm^2.

The choice of anodes was very important, since if some of them failed, flooding of the inside of the bulb or entry of water into the plant could result. These anodes were chosen to be indestructible, and are made of tantalum covered with a 50µm layer

of platinum.

In principle, a layer of platinum a few microns thick would be sufficient to allow these anodes to function well, so the thickness of 50μm does in fact give an ample safety factor. A set of identical anodes with a 5μm platinum coating has been installed in one turbine for test purposes.

It should also be noted that the platinum does corrode with alternating current, so that it is important for good anode life to check for proper operation of the rectifiers periodically.

4.1.1.3. The choice of the current density which determines the potential of the metal with respect to the electrolyte is important. It has been observed that while an insufficient lowering of the potential of the metal, $E_m > -800$mV, does not protect the metal effectively, too great a reduction, $E_m < -1200$ mV subjects the paint film to large electric stresses and may destroy it by saponifying the binder. The potential must thus be adjusted between these two values.

It should also be noted that the potential cannot be changed instantaneously: the phenomenon of polarization takes place slowly. Each change in the settings must be accompanied by a stabilization period in the order of a week.

Operation of cathodic protection in seawater causes formation on the metallic surface of a deposit of positive ions from the electrolyte, magnesium, calcium, and sodium, which precipitate as carbonates and sulfates.

This so-called "calco-magnesia" deposit is an insulator; its /15
appearance, density, and adherence are functions of the current density (the deposit is hard, insoluble, and sticks tightly to

the metal at the low current densities used at the Rance plant).

On painted surfaces, it closes over cracks in the coating to a certain extent, and decreases the protective current. It can last several weeks after this current stops, and thus would contribute to protection of the metal during a power failure or improper adjustment of the current.

4.1.1.4. In 1966 the first potential measurements were started on the turbines of group A and in April, 1966, cathodic protection was begun on this group with a current slightly less than 3 A for 12 anodes.

A first difficulty appeared immediately because of the voltage drops along the conductors of unequal lengths. It was impossible to obtain equal current flows among the anodes of the different turbines of a group, and it was necessary to insert variable resistors at each turbine so these voltage drops could be adjusted.

This difficulty overcome, we could observe that for a given turbine the current density at the anodes is perturbed perceptibly by various factors:

— Installation of cut-off cofferdams: explained by the size of their metallic mass, which significantly modifies the potential distribution.
— Water temperature: specialists in ship-hull protection assume that the current density doubles when the water temperature increases 20°.
— Whether the turbine is stopped or operating, and even the type of operation, especially the direction of the water flow. This cause of perturbation, also met in the protection of ships, where the current density varies by a factor of two

depending on whether the ship is dead in the water or under way, can be explained as follows: for a low-resistance electrolyte such as seawater the current density required for cathodic protection depends almost entirely on the polarization of the metal surface at defects in the coating. The oxygen present in the water produces a depolarization which, to be overcome, demands a steady flow of current whose size is a function of the possibility for oxygen diffusion near the metal; this possibility is obviously strongly affected by the velocity of the water flow.

4.1.2. Gates

4.1.2.1. The remarks about the mediocre durability of the paint protecting the gates and the difficulties experienced in repairing this paint led our engineers in 1966 to decide to protect the metallic structures of the gates by cathodic protection by imposed current.

As for the turbines, this protection was put into operation in February-March, 1968. The study was carried out by the special service of Gaz de France and the system was created during 1967.

For each gate, the system consists essentially of four anodes (two on the seaward side, two on the basin side) supplied from two transformer-rectifiers which can provide 40 A. One system supplies the seaward anodes, the other those on the basin side. Two potential test-points, one on each side of the gate, allow one to monitor the adjustment of the protection.

The anodes, composed of titanium cylinders held by aluminum bronze anode supports, are sealed in the piles on either side of each top hole at height -2.50.

The gate sill is at -4 and the height of the superstructure is 10 m, so that a variable part of their surface is uncovered each day by tidal motion. From this constant change in cathode surface there can result a variation in current density which at low tide may exceed the critical level for attack on the paint. To prevent this danger, two manometer capsules regulate the operation of the protection system according to the level of the water on each face of the structure.

4.1.2.2. As was mentioned above, the protection of these gates uses currents which range from 4 to 61 A, depending on the condition of the paint.

As we have said in enumerating the precautions to be taken in putting together systems, these gates were electrically insulated from the reinforced concrete and from the roller rails and the stainless-steel rollers. The spindles carrying the rollers were subject to severe corrosion. We believed that the good quality of the reinforced concrete, shown by the low currents through the reinforcing rods, would let us use a very small supplementary current here to make the attack on the spindles disappear if the insulation between the frame of the gate and the guide rails were removed.

Trials have confirmed our idea, and the rails and spindles have been protected by increasing the output of the rectifier of the gate, without supplementary equipment.

Since cathodic protection of these gates was instituted, /17
that is, since 1968, mechanical overhauls, accompanied of course by repainting, have been carried out at four-year intervals without corrosion damage ever requiring us to increase the frequency of these repairs.

I shall conclude the discussion of the gates by saying that one can see on the obviously degraded sections that the calco-magnesium deposits produced by the cathodic protection have taken the place of the paint, and cover absolutely sound metal. A secondary advantage of this basic deposit is that it suppresses oxidation of the threads of the screws holding the seals, which are still not difficult to remove after several years of marine immersion.

4.1.3. Lock

The remarkable quality of the results obtained by cathodic protection of the turbine-bulb systems and of the gates led us to install this protection on the lock gates in March, 1970.

Without cathodic protection, very many instances of corrosion were observed:

— Severe corrosion of the tubular frames and posts, of ordinary steel, for the small gates in the aquaducts, sometimes penetrating completely through.
— Corrosion of the aquaduct gratings, made of ordinary steel painted with a vinyl paint.
— The lock gates are vertical, and the seal at the pivots is a ring of mercury into which one ordinary-steel cylindrical wall dips; this plate literally fused because of the electrolytic effects. The mercury was removed and a very thick compound used, which solved this problem.

During this second period, cathodic protection with consumable anodes has reduced corrosion of the aquaduct gates, except below the frames where shells continue to accumulate. We are going to put an anode in the lower part to protect this area.

The aquaduct gratings, which are unaffected by the cathodic

protection, have continued to corrode, despite the paint. We are going to connect them to the gates to protect them.

The corrosion of the gates themselves has been stopped in the spots where the paint had been removed.

4.2. Cathodic protection by soluble anode /18

It is used only on a single category of parts: the gates of the lock aquaduct, as we have just mentioned.

Since they are too far from the gates of the lock to be inside the field created by those anodes, very localized protection is provided by zinc anodes which are inspected regularly for loss of mass, and which are replaced regularly at a frequency which we can ignore because of the ease with which this can be done.

CONCLUSION

We have just seen that the dangers of metal corrosion in seawater have not escaped the designers of the Rance plant. By large-scale studies and by utilization of new methods and selected materials, they have done their utmost to solve the problem as well as possible in the light of present knowledge.

We should like to give ourselves a small complement: the good results obtained are due in large degree to painstaking preparation and to the many investigations devoted to the Rance project, and to the excellent working relationships which have developed among all those involved, both in the studies and in the construction and operation.

Also, we would like to recall the conclusion of an internal note written by M. Marolleau, former head of the Rance plant.

"After eight years of operation, it can be said that cathodic protection plays an essential part in the proper functioning of the Tidal-Power Plant, efficiently protecting carbon steel and suppressing pitting corrosion, found on certain stainless steels, in a system of some 12,000 metric tons immersed in seawater.

This protection allows a considerable spacing out of repainting cycles, which contributes to a reduction in machine down-time, and appears as a gain in the energy produced by the Rance Tidal-Power Station."

Translated for National Aeronautics and Space Administration under contract No. NASw 2483, by SCITRAN, P. O. Box 5456, Santa Barbara, California, 93108.